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13. ABSTRACT *(Maximum 200 words)*

The three objectives of this research were to study and create new technologies for: (1) identifying damage in complex structures; (2) mitigating damage in structures built from composite materials; and (3) controlling smart material systems and structures. Model-independent, non-destructive evaluation methods for complex structures have been developed to detect incipient damage, delaminations and disbondments, and to allow structures to perform self-diagnostics. A patent has been granted for a method improving the impact tolerance and penetration resistance of composites. Several new technologies were developed to control smart material systems and structures. A compact actuator, producing both large displacements and forces, was designed, built, and tested for helicopter vibration and noise control. A theoretical model of wave propagation and energy dissipation in joints was developed. A new signal processing technique was developed for arrays of sensors to directly create a signal for the modal content of the structural vibration. A method of damage detection for complex structures that does not depend on an analytical model of the structure has been developed and experimentally verified.

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SMART MATERIALS, STRUCTURES, AND MATHEMATICAL ISSUES FOR ACTIVE DAMAGE CONTROL

FINAL PROGRESS REPORT

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Smart Materials, Structures and Mathematical Issues
for Active Damage Control

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I. Executive Summary: Technical Highlights

The three objectives of this research were to study and create new technologies for:
(1) identifying damage in complex structures; (2) mitigating damage in structures built from composite materials; and (3) controlling smart material systems and structures.

Four model-independent, non-destructive evaluation methods for complex structures have been developed. The impedance-based real-time technique can sense incipient damage in a localized area. The laser Doppler vibrometer technique uses membrane vibrations to quickly detect delaminations and disbondments over large areas. By adding active tagging particles during composite manufacturing, the resulting structures can be tested with a new in-situ active tag technology. Structural self-diagnostics algorithms were developed to detect damage by quantifying variations in damping and time response.

In the second research area, damage mitigation in composites, the impact tolerance and penetration resistance of composites were improved by embedding super-elastic shape memory alloy (SMA) to efficiently dissipate and distribute impact loads. A U.S. patent has been granted to Virginia Tech for this technology. This research activity is most directly applicable to U.S. Army needs - allowing advanced composites to be developed which provide improved protection for troops while maintaining low weight per square foot. These research results have also generated numerous technology transfer activities.

Several new technologies were developed to control smart material systems and structures. A compact induced-strain actuator, producing both large displacements and forces that can be used in individual rotor blade control for reduced vibration and noise, was designed, built, and tested. Trim tabs for helicopter blade control have also been developed, built, and tested. A fully adaptable modal sensor for structural control has been designed, built, and tested.

In addition to these technology development efforts as part of this research project, we have created several purely analytical studies which have added to the general knowledge base regarding intelligent material systems, and structures. We have developed a theoretical model of wave propagation and energy dissipation in joints. A new signal processing technique for arrays of sensors to directly create a signal for the modal content of the structural vibration has also been developed.

II. Scientific Progress and Accomplishments

The three objectives of this research were to study and create new technologies for:
(1) identifying damage in complex structures; (2) mitigating damage in structures built from composite materials; and (3) controlling smart material systems and structures. A brief overview of the progress and accomplishments is presented in the following sections of this final progress report.

Identifying Damage in Complex Structures

Electrical Impedance Measurements

A new impedance-based technique, which provides a practical means for the health monitoring of complex structures, was investigated and developed. The two main benefits of this technique are sensitivity to incipient damage and a localized sensing area. New proof-of-concept demonstrators were tested to ensure the applicability of the technique to a wide array of complex structures. Also, the temperature dependency of the technique, due to the PZT capacitance change, was investigated. To solve this problem, a software correction procedure, eliminating the temperature dependency, was established. Finally, the localization effect due to energy dissipation in non-conservative joints and material damping was investigated. Theoretical models are currently being developed.

The real-time implementation of this technique relies on a simple scalar damage index that can be easily interpreted. Using this damage index in conjunction with a damage threshold value, the approach can warn the operator, in a green/yellow/red light form, whether or not the threshold value has been reached. A damage index that is not affected by environmental effects was established based on statistical analysis and signal processing, making the damage index more stable under all types of environmental conditions.

Laser-Based Qualitative Health Monitoring

This new non-destructive evaluation (NDE) technique is based on the local membrane vibrations of debonded areas which will produce higher vibrations that can be read with a scanning laser Doppler vibrometer. Piezoelectric actuators bonded on the surface of the composite panel (wrapping) and driven by a chirp sine voltage provide the structure with a broad-band excitation. The spectral band is deliberately chosen such that the debonding area (if there is any) of the composite wrapping will experience a flexural vibration much higher in level than that of the well-bonded area. The employment of narrow-band chirp sine excitation, rather than conventional broad-band random excitation, significantly improves the signal-to-noise ratio of the image through the increase of the spectral power density of the energizing source. The scanning laser Doppler vibrometer can quickly create an image of the flexural vibration level of a composite surface of large area, revealing the weak-bonded or debonded as spots of high vibration. A proof-of-concept prototype of a solid concrete block has been made and fully tested. It has been demonstrated that a small debond (a few square centimeters) between the composite patch and

the concrete block can be easily identified by its relatively large flexural vibration level (a contrast ratio of 10) on the laser scanning image. This promising technique can also be applied to the delaminations in composites.

Theory for Self-Diagnostics

Two self-diagnostic methods were developed: the first examines the structural damping as a measure of damage, while the second does not use a model of the structure and is based on the beat phenomenon.

Inverse eigenvalue methods for identifying a damping matrix for use in self-diagnostic applications have been derived. A change in the global damping matrix can be related to a change in torque on a bolted joint. With this in mind, we performed a computational study on the numerical stability of computing damping matrices using inverse methods. Initial research showed that a substantial increase in computational time can be achieved by matching algorithms to parallel computing methods. In further examinations, the linear algebra of a matrix polynomial was used to solve an inverse eigenvalue problem, resulting in an expression for the structure's damping matrix. This damping matrix was then compared to that of the same structure in its damage state to provide an indication that some damage had occurred. Time history data is recorded, and a standard realization algorithm is applied to estimate the eigenstructure, which is then fed into an inverse eigenvalue problem algorithm to produce an estimate of the damping matrix. This technique has been applied successfully to a bolted structure in the laboratory.

A time domain procedure was also developed which relies on the measured time response of a healthy, yet unmodeled structure due to a simple harmonic input. This signal was then compared to the measured time response for identical input of the structure after some local damage was introduced. These two signals, healthy and damaged, were then compared by subtracting them from each other. The resulting beat phenomena provide an indication of the existence and extent of damage reflected in local mass and/or stiffness changes. The use of this algorithm was successfully applied to the change in mass in a helicopter blade section without using or requiring a model of the blade.

Mitigating Damage in Structures Built from Composite Materials

SMA Hybrid Composites for Improved Impact Tolerance

The goal of this research is to improve the impact tolerance of various SMA hybrid composites at both low and high velocities. The effect of low volume fractions (3% and 6%) of embedded Nitinol fibers on the impact-absorbing ability of graphite composites was investigated. It was found that the peak loads and stiffness were influenced by the SMA fibers, but the load deflection after peak load was considerably modified. The SMA's high strain energy ability allows it to absorb impact energy through strain, pull-out, and by distributing impact load to undamaged regions of the graphite. Increases of 23% and 41% in absorbed energy over the bi-directional plain graphite lay-up was observed with 3% and 6% volume fractions of unidirectional SMA fibers, respectively. The SMA hybrids offer significant increases in energy-absorbing ability and

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preventing penetration. They do not, however, offer increased damage resistance. Therefore, they have potential use in applications where penetration resistance is imperative and residual strength is not critical.

Ballistic Testing

A significant increase in energy absorption has been observed by embedding small amounts of superelastic shape memory alloy (SMA) wires in thin graphite/epoxy composites under quasi-static loading and low velocity impact (14 ft/sec). The objective of this research was to investigate the energy absorption capabilities of SMA hybrid composites at high-velocity impact (1000+ ft/sec). In order to obtain realistic results, 12 x 12 inch panels with cross-ply SMA configurations were tested with projectiles fired from a 9 mm handgun. It becomes more difficult to implement the energy-absorbing capabilities of SMA fibers at ballistic velocities, with the SMA (1.2% by volume) absorbing only 4% of the energy. This reduced performance is due to high strain rate effects, constituent strain incompatibilities, gross fiber pullouts, and stress concentrations created by the wires embedded in the composite. It has been determined that the best location for a high-strain impact-resistant hybrid component is on the back of the structure where it is less constrained from straining. By embedding 1.2% of SMA fibers on the back face in a more compliant high-performance polyethylene material (Spectra), a 24% increase in the energy absorbed was observed.

Modeling of Impact Energy Absorption

Research at CIMSS has shown that SMA hybrid composites offer significant increases in energy absorbing ability, thereby preventing penetration. Thus far, research has been mostly experimental. The goal of the research was to develop theoretical explanations through understanding the energy transfer mechanisms by analytically modeling the impact event. A model based on the energy balance principle, including the local contact deformation, the global bending deformation, and the transverse shear deformation, was developed. It was found that the impact energy absorption can be nearly doubled due to stress-induced martensitic phase transformation.

Controlling Smart Material Systems and Structures

Hydraulic Displacement Amplifier for HHC of Rotor Blades

The implementation of individual blade control (IBC) using induced-strain actuators (ISA) for vibration reduction in helicopter rotors is under investigation. Among the actuation options for rotor blade vibration control, the solid state electro-mechanical devices - such as induced-strain actuators (ISA) - were proposed because of their compactness, self-containment, high energy and power densities, and remote powering. Their main shortcoming is the low output displacement. The principle of hydraulic displacement amplification was proposed to overcome this drawback, and a full-scale proof-of-concept demonstrator was constructed and tested. Static tests have shown good kinematic response, but highlighted the necessity for reducing the Coulomb friction between hydraulic seals and cylinder bores. Dynamic tests, performed with a pair of 1/4 power,

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low-cost PMN stacks and a small high-voltage power amplifier, have shown good dynamic response up to 20 Hz. Hence, the principle of utilizing induced-strain actuators with hydraulic amplification for realistic servo-tab actuation was verified through experimental testing. Based on the knowledge gained from the demonstrator, a new actuator optimizing weight, volume, and performance was proposed, which could be built to a fully operational prototype in cooperation with the aeronautics and aerospace industries.

Researchers at CIMSS have further developed improved concepts for the actuation of rotor blade flaps and tabs to be used for reducing helicopter rotor blade vibrations. For flap actuation, a large-amplitude rotary induced-strain (LARIS) actuator concept has been proposed. The LARIS actuator is a high-frequency piezo-active device aimed for higher-harmonic individual blade control (HC-IBC). This actuator uses the torsion-warping coupling of a thin-wall open tube. Since the actuator output increases directly with its length, the LARIS concept seems to be ideally suited for rotor blade applications, in which large actuator lengths can be accommodated along the blade spar. The LARIS concept can be used in both trailing edge and tip-mounted flaps.

For tab actuation, a shape memory alloy (SMA) composite tab concept has been proposed. This tab is a low-frequency device using thermo-active SMA materials. The SMA tab allows incrementally adjustable trimming of the rotor blade aerodynamics at various flight regimes. This will improve the blade tracking and reduce the overall vibrations due to blade imbalance. Both concepts have been experimentally tested and patent disclosures have been filed.

Adaptive Modal Sensors

Numerical and experimental investigations were performed to verify a method to create modal sensors for beams. A modal sensor is created by attaching rectangular segments of piezoelectric film to the beam and multiplying the segment outputs by certain gains so that the weighted combinations of the outputs approximate the modal coordinates of the vibrating beam.

The method has been tested on a simply-supported beam. It is shown that combining the outputs from the segments with correct weights results in a sensor that is sensitive to only a selected mode of vibration of the beam and filters out the other modes.

A significant breakthrough in signal processing for structural vibrations was subsequently created. Using a Laplace transform technique, the modal sensors can be made adaptive - as the structure changes, the desired modal coordinate is continuously tracked. This makes possible robust modal sensors to be used for structural control.

Modeling Thermoelastic Response of Piezoceramic Devices

Modeling: Many applications of smart structures technology require that closed-loop response performance be unaffected by rather large changes in ambient temperature. Hence, temperature effects on piezoceramic materials have been examined and two distinct effects have been modeled: (1) the pyroelectric effect; and (2) the coupling between temperature changes and vibratory

responses of a structure. The coupling results from the explicit dependence of the thermal boundary value problem on the structural deformation.

Control: By developing the models which incorporate these effects, large temperature changes on the structure and actuator are taken into account in the control system design. An optimization routine is used to find a suitable placement for the sensors and actuators. Assuming full-state feedback, an optimal solution is obtained for vibration suppression. A classical control solution using feedback is also given. Simulation results show that thermally-induced vibrations can be controlled using currently available smart structures technology, provided temperature effects are properly modeled and accounted for in the closed-loop controller. The result is a structure that can withstand a thermal load without excessive vibration.

III. Technology Transfer

In addition to technical contributions, significant progress has been made in both the outreach and technology transfer components of our program. In the outreach component, our summer undergraduate research internship program annually attracted top undergraduate students, giving them a substantial research experience in the field of smart structures and encouraging them to attend graduate programs. This program was conducted each summer from 1992 to 1997, and several undergraduates also participated in a similar program during selected academic years. More detailed information about these programs is found in later sections of this report.

During the course of this research endeavor, members of the CIMSS research team have visited with many U.S. companies and government laboratories to encourage the use of active structures technology. Below are listed some specific examples of CIMSS technology transfer efforts during the course of this project.

<u>More Recent Contacts</u>

- Vehicle Structures Directorate, U.S. Army Research Laboratory - currently incorporating the CIMSS hydraulic displacement amplifiers which enable stacked piezoelectric elements to actuate helicopter rotor blade flaps in the rotorcraft testing facility at the Vehicle Structures Directorate.
- U.S. Navy - began project to demonstrate non-destructive evaluation using sensori-actuators to determine the health of the composite repair patch on Pier 11 at the Norfolk Naval Base.
- U.S. Army Corps of Engineers Construction Engineering Research Laboratories - locating damage in composite-reinforced masonry structures.
- U.S. Army Corps of Engineers Construction Engineering Research Laboratories - locating damage in glass fiber-reinforced composites.
- SCITEX Digital Printing, Inc. - providing methods for modeling the piezoelectric actuator in the high-speed print-heads of commercial printers to enable them to print at up to 10 times their current rates.
- Axiom Composites - investigated economic feasibility of using shape memory alloys to improve impact resistance of composite repairs applied to civil structures.
- Gentex, Inc. - investigating using shape memory alloys to reinforce composite helmets.
- Lear Corporation - investigating feasibility (both technical and economic) of using smart materials to provide vibration and noise control in automotive applications.
- Advanced System Technology Group (Phantom Works) at McDonnell Douglas - advised engineers on techniques for damage detection in composite helicopter rotor blades.
- CIMSS Actuator Study - developed a solid-state actuator study for commercially-available actuators. To date, this study has been distributed widely to industry and government labs and continues to be highly requested.
- Allied Signal - improving the ballistic impact resistance of composite structures.
- Electric Power Research Institute (EPRI) - non-destructive evaluation in power plants using sensori-actuators.
- United Technologies Research Center (UTRC) - exchanged technology on actuator modeling. UTRC now uses the CIMSS-developed impedance-based damage detection method.

- Monroe Manufacturing - is considering using SMA's to control out-of-balance in their washing machines.

Other Army Contacts

CRDA with ARL	(Bernard Halpin)
USACERL	(Robert Quattrone)
Vehicle Structures Directorate	(Kevin O'Brien)
AATD	(Donald Merkley)
NASA	(Robert S. Rogowski)
ARL, Materials Directorate	(Gary Hagnauer)
Army Tank - Automotive Command	(W. Bryzck)
NASA-Ames (U.S. Army Aeroflight-dynamics Directorate)	(Robert Ormiston, Stewart Hopkins)
Army Aviation & Troop Command	(Y.H. Yu)
ARL	(T.W. Wright, Bruce Burns, Danny Hoad)
TACOM	(Roger Wehig)
NASA - LaRC Aerostructures Directorate	(Gary Farley)

Other Industry Contacts

Boeing Helicopter, Philadelphia	EDO Corporation
Ford Motor Company	Martin Marietta Laboratories
Chrysler Corporation	ICI Wilton Materials Research Center
General Motors Corporation	General Dynamics
Allied Signal Corporation	Lockheed-Martin
Staged Vibration Corporation	Hercules Aerospace Company
BF Goodrich	U.S. Nitinol
American Research Corporation of Virginia	Owens-Corning
Defense Research Consultancy, Ltd., UK	DSB Associates
ABB Ricerca, Italy	Clark-Schwebel, Inc.
Forte Technologies, Inc.	Composites Institute

Lawrence Livermore National Laboratory

Catepillar, Inc.

Metalurgica Sabat, Spain

Olofsson Machine Tools, Inc.

E.I. DuPont de Numours and Company, Inc.

Electric Power Research Institute

Mitsubishi Materials Corporation

Telephonics Corporation

BDM Federal, Inc.

E-Systems, Inc.

Westinghouse Naval Systems

Westinghouse Electric Corporation

DLR (Germany)

Aerospatiale (France)

TRW

General Dynamics

Foster-Miller, Inc.

United Technologies Research Center

Rotocraft Industry Technology Association (RITA)

Jet Propulsion Laboratories

FMC

Lord Corporation

McDonnell Aircraft Company

Memry Corporation

Monroetech

CSA Engineering

Interplastic Corporation

PPG Industries, Inc.

Creative Pultrusions

TPI, Inc.

Reichhold Chemicals, Inc.

Byelocorp Scientific Corporation

AVX Corporation

3M

Tracor

AT&T Bell Laboratories

Walt Disney Imagineering

Martec Limited (Canada)

Saphikon

M&M Mars

Sandia National Laboratories

MPB Technologies, Inc.

Raychem Corporation

Building Research Institute (Japan)

Inland Fisher Guide Division, General Motors Corporation

McDonnell Douglas

Atlantic Research Corporation

Measurements Inc.

Bell Helicopter Textron, Inc.

Boeing Defense and Space Group

PCB Electronics

IV. Publications

Directly as a result of ARO sponsorship, the following manuscripts have been submitted or published during the course of this award:

Journal Publications

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V. Education, Outreach, and Personnel

Education and Outreach Program Summary

One of the objectives of this URI program was to educate graduate students and researchers in the multi-disciplinary aspects of smart material systems and structures. In keeping with this, investigators at CIMSS have sought to develop a wide range of educational programs for graduate, undergraduate, pre-college, and minority students on the issues of smart material systems. Investigators at CIMSS have also sought to incorporate the university's mission of service through this URI program by developing short courses and public school programs, by disseminating computer codes, and by producing an intensive survey of commercially-available actuators.

Educational Program Highlights

Undergraduate Research Internships Program

The objectives of this ongoing program are to introduce undergraduate students to the field of intelligent material systems; to demonstrate the interdisciplinary nature of the area and the wide range of opportunities available; to introduce students to the research process and the challenges offered by graduate study; to foster growth in research-related skills; and to attract the best students to our graduate research program. Undergraduate Research Internships were awarded to numerous students during each year of the ARO-URI program at Virginia Tech (see list in Personnel Section of this report).

Minority Program

Responding to the need to attract and retain students from under-represented groups to science and engineering, CIMSS has made an effort to provide funded research opportunities for minority students and faculty as part of this ARO-URI program. Students and faculty from historically-black colleges and universities (HBCUs) and minority institutions were invited to CIMSS to learn more about the sciences and new technologies associated with intelligent material systems and structures and to work on collaborative projects and proposals. Several invited speakers (Dr. Carolyn Meyers, Dr. Jane Daniels, Dr. Cornel West) were brought to campus with support from CIMSS to address issues related to minorities in science and engineering.

Numerous undergraduate students representing minorities in science and engineering received research internships at CIMSS (see list which follows in Personnel section of this report) during the course of this URI program. One of these students, Mr. Brian Childs, a Mechanical Engineering major from California State Polytechnic University at Pomona, used his ARO summer undergraduate research project at Virginia Tech in competition at the National Society of Black Engineers national convention in March, 1996. Brian won first place in the Western Regional competition, and then went on to place second on the national level for his research at CIMSS involving a high-frequency vibration signature for non-destructive evaluation of complex precision parts.

Visiting Scholars Program

The purpose of this program has been to provide an opportunity for scholarly individuals to visit the Center for various periods of time to collaborate with Center faculty, staff, and students, to present lectures, to perform specific research activities, and/or to collaborate on scientific publications, proposals, etc. Funding for this program through the ARO-URI has helped to ensure that the appropriate flow of information is maintained to and from CIMSS regarding fundamental knowledge, new developments, and the current state of knowledge. The following are examples of some of the Visiting Scholars visiting CIMSS in the past several years.

Dr. Mike Friswell, a prominent British scholar, from the Department of Mechanical Engineering at the University of Wales in Swansea, United Kingdom, visited CIMSS from March to August, 1997. His objective was to learn the state-of-the-art in smart structures and vibration control in the U.S.

Dr. Zhongwei Jiang, Associate Professor, Department of Mechatronics and Precision Engineering, Tohoku University, Sendai, Japan, visited CIMSS for 10 months in 1997 to further develop his research activities in smart material systems and structures.

Dr. Young-Kong An, a recent graduate from Yokohama National University, Japan, visited CIMSS in 1996 and 1997 to extend his work on smart materials and structures.

Dr. Serge R. Gorodkin, Senior Researcher, Laboratory for Polarized Media, A. V. Luikov Heat and Mass Transfer Institute, and Research and Development Engineer, MART, Minsk, Byelorus, visited CIMSS during the Fall of 1995 to perform research regarding the composition and use of magnetorheological fluids.

Dr. Zoya Novikova, Research Scientist, Heat and Mass Transfer Institute, Academy of Sciences of Byelorus, Minsk, Byelorus, visited CIMSS during the Fall of 1995 to perform research regarding the refinement and application of magnetorheological fluids.

Exchange Student Program

In this program, CIMSS hosted students for brief research visits while they were completing degrees at their home schools. The program was established in response to requests from international universities that do not yet have the facilities and expertise to carry out extensive experimental investigations in the area of smart materials and structures. Through funding from the ARO-URI program, CIMSS has provided the necessary administrative and technical support, as well as the laboratory space and facilities, to perform the desired projects. The following are examples of some of the Exchange Students visiting CIMSS in the past several years.

Ms. Marita Toth Kulti visited CIMSS from May to July, 1997, as an exchange student in Systems Engineering from the Royal Institute of Technology in Stockholm, Sweden. Marita carried out experiments in the distributed sensing of structures.

Mr. Karsten Meissner visited CIMSS from April to July, 1997, as an exchange student in Mechanical Engineering from the University of Paderborn, Germany. He was interested in using piezoelectrics to improve control.

Mr. Gildas Daniel visited CIMSS from April to July, 1997, as an exchange student in Materials Science from the University of Rennes, France. He was particularly interested in large-scale production applications of smart material systems.

Mr. Jasper Zuidervaart, a graduate student in Mechanical Engineering at the University of Technology Eindhoven, in The Netherlands, visited CIMSS in the summer of 1996 to work on a project involving smart composites using shape memory alloys (SMAs). His work at CIMSS involved experimental validation of the constitutive model of SMAs and determination of the physical parameters used in the model. His work coupled with other investigations underway involving SMAs for use in impact-resistance, such as bullet-proof vests, bullet-proof rotor blades, and armored fuel tanks.

Mr. David Crisinel, a Physics major from the Swiss Federal Institute of Technology (EPFL), in Lausanne, Switzerland, visited CIMSS in the Fall of 1995 to investigate the effect of static loading on the non-destructive evaluation technique developed at CIMSS.

Ms. Alessandra Sermoneta visited CIMSS for about 6 months in 1994 from the Aerospace Department at the University of Rome, Italy. She worked on projects involving the dynamic analysis of active structures with multiple actuators.

Graduate Course

Responding to the lack of graduate courses available to support the relatively new area of intelligent material systems and structures, a graduate course entitled, "Mechanics of Smart Material Systems," was developed and taught in 1992, 1994, and 1996. In the course, students are introduced to the concept and history of intelligent material systems, define the current state-of-the-art, and study many of the materials that are components of intelligent material systems. Students from mechanical engineering, aerospace engineering, and engineering science and mechanics have participated in this course. Developed as part of the ARO-URI program, this course represents the country's first graduate-level course in the area of intelligent material systems and structures.

Graduate Student Conference

CIMSS hosted the first Graduate Student conference on Smart Material Systems and Structures at Virginia Tech in Blacksburg, VA, on April 2-3, 1993. The intent of this first student-oriented conference was to provide a casual and open forum for discussions and presentation of current research results by graduate students. Other objectives of the conference were to provide an opportunity to promote friendships and acquaintances within the intelligent materials community and to become acquainted with the current state of research in the field.

Over fifty students attended the first conference, including 30 from Virginia Tech, 9 from University of Maryland, 6 from Vanderbilt, 2 from Duke University, and 4 from Purdue University. Participants attended presentations and enjoyed an evening barbecue and morning continental breakfast.

The second Graduate Student conference on Smart Material Systems and Structures was held at the University of Maryland, with numerous students from Virginia Tech attending.

Outreach Program Highlights

<u>International Conferences</u>

CIMSS commitment to outreach and technology transfer during the course of the ARO-URI program is evidenced by the Center's organization of numerous international conferences. In 1992, CIMSS organized the Conference on Recent Advances in Adaptive and Sensory Materials and Their Applications (Blacksburg, VA, April); in 1994, CIMSS organized the 2nd International Conference on Intelligent Materials (Williamsburg, VA, June); in 1995, CIMSS hosted the 6th International Conference on Adaptive Structures and Technologies (Key West, FL, November); and in 1997, CIMSS organized the Third ARO Workshop on Smart Structures (Blacksburg, VA, August).

<u>Public School Programs</u>

Tour de TECH

Tour de TECH (now called Explore Tech) is a comprehensive science and engineering exposition for public school children that has been organized for each of the past 5 years by CIMSS, an ARO-URI Center at Virginia Tech. More than 5,000 school children (k-12) attend the expositions in Blacksburg and Richmond, VA, each year in April and May.

Laboratory Experiences for Girls

Middle-school girls from Blacksburg have visited the CIMSS lab to learn the engineering concepts necessary to build very simple, low-cost speakers using piezoelectric ceramic actuators attached to a large plate, such as a plexiglass sheet. This new concept could be used to replace the speakers in automobiles and buildings, giving a new definition to "surround sound". The speakers designed and built by the middle-school girls were demonstrated for other school-aged children at Tour de TECH in Blacksburg in 1995 and 1996.

High-school girls from Richmond, VA, travelled to Blacksburg in 1996 to participate in a 2-day engineering camp at CIMSS. The students created two novel engineering systems based upon state-of-the-art research in solid-state actuation. Specifically, the two projects involved: a) micro-robots using piezoelectric actuators (motors) for "legs", and b) a solid-state stereo speaker

using piezoelectric ceramic actuators. The projects were demonstrated by the girls at the Tour de TECH exposition in Richmond in May, 1996.

Short Course and Technology Overviews

One of the goals of the ARO-URI program at CIMSS, Virginia Tech, was to keep industries and government laboratories informed of new developments and the current state of knowledge relating to intelligent material systems and structures. To meet this aim, a short course on Smart Material Systems was developed and presented by various investigators during the course of this project.

Dr. Craig Rogers and Dr. Dan Inman annually participate in technology overview presentations at the annual SPIE conference. These one-hour overviews are designed to support the needs of applied scientists and practicing engineers working in the area of smart structures and materials. Participation is open to all attendees of the Annual SPIE Symposium on Smart Structures and Materials.

Dissemination of Computer Codes

Through the ARO-URI program, CIMSS has developed computer software packages to assist with the design of intelligent material systems and structures. The software packages are available to any research institute, government agency, or industry, upon request.

DAISA (Dynamic Analysis of Induced Strain-Actuated Beams) is a user-friendly, menu-driven software package for the static and dynamic analysis of beam structures actuated with surface-bonded PZT actuators. This software can assist with the preliminary design of piezoelectrically-actuated structures for applications such as vibration and shape control.

SMAAD (Software for Shape Memory Alloy Actuator Design) is a user-friendly, menu-driven software package for the theoretical analysis of shape memory alloy (SMA) actuators. The program incorporates the thermomechanical constitutive model of SMAs developed at CIMSS to calculate the force-temperature and the stroke-temperature relations as well as the stress-strain relation at a given temperature. Many design parameters of an SMA actuator can be implemented in the program.

Actuator Study

During the course of the ARO-URI program, investigators at CIMSS performed a study of published literature and vendor information for commercially-available piezoelectric, electrostrictive, and magnetostrictive actuators. Static and dynamic operation conditions were considered. Output energy, energy densities, and conversion efficiency were evaluated and compared. The overall performance of induced-strain actuators was found to vary widely from vendor to vendor, and even from one model to another. These variations are attributed to progress in active material technology and in the mechanical construction of induced-strain

actuators based on these materials. To date, this study has been distributed widely to industry and government labs, and it continues to be highly requested.

<u>World-Wide Web Page</u>

One of the objectives of the ARO-URI program at CIMSS is to effectively disseminate information about the research activities and opportunities available in smart materials and structures. Access to this information on the worldwide web is now available at http://www.cimss.vt.edu. The CIMSS web page includes links to Virginia Tech, the Mechanical Engineering department, the Mechanical Systems Laboratory (MSL) founded by Dr. Dan Inman, as well as to many research organizations and government agencies (ARO, NSF, CERL) currently funding research in intelligent material systems and structures.

Scientific Personnel Supported

<u>Faculty/Principal Investigators</u>

Dr. Daniel J. Inman
Dr. Harley H. Cudney
Dr. Craig A. Rogers
Dr. Harry H. Robertshaw
Dr. O. Hayden Griffin, Jr.
Dr. Rafael T. Haftka
Dr. Ayo Abatan
Dr. James S. Sirkis
Dr. David Lieberman
Dr. Carolyn Meyers
Dr. Jan Holnicki-Szulc
Dr. M. H. Kadivar
Dr. Layne T. Watson

<u>Research Scientists and Research Associates</u>

Dr. Zaffir Chaudhry
Dr. Victor Giurgiutiu
Dr. Frederic Lalande
Dr. O. Song
Mr. Fanping Sun
Ms. Linda Vick
Dr. J. H. Lee
Dr. Chen Liang

Graduate Students/Lab Assistants

Osama Ashour
Eric M. Austin
John Ayres
Steve Booth
Clay Carter
Jens Cattarius
Daniel G. Cole
Craig Dempsey
Roger Ellis
Jaime Esteban
G. Fagan
Prasad Gade
Sucharita Gopalakrishnan
S. Hsu
Hongyu Jia
David Kiel
Thomas Kiesling
Karthik Krishnamurthy
M. Lamanderson
Mark Lin
Y. Liu
Jeffrey S. N. Paine
L. M. Parietti
Gyuhae Park
J. Pascoe
Debbie Pilkey
Brett J. Pokines
Vinod Raju
Ramanathan Ramakrishnan
Razvan Rusovici
Manish Sabu
P. K. Sensharma
Mark Sensmeier
Tom Snyder
Anton Sumali
Peter Tappert
P. M. Tavernise
Jeff Tucker
Suwei Zhou
Jasper Zuidervaart

Undergraduate Research Interns

1992:   Eric Flint, Aerospace and Ocean Engineering, Virginia Tech

1993:   Chris Waldhart, Aerospace and Ocean Engineering, Virginia Tech
Tony Ganino, Mechanical Engineering, Virginia Tech

1994:   Tim Joseph, Mechanical Engineering, Virginia Tech
Robert Weigel, Mechanical Engineering, University of Wisconsin - Platteville

1995:   Mike Abbot, Mechanical Engineering, Virginia Tech
Matthew Kelton, Mechanical Engineering, Virginia Tech

1996:   Richard Stendardo, Aeronautical and Mechanical Engineering, Boston University
Brian Sapp, Mechanical Engineering, Virginia Tech
David Longanbach, Mechanical Engineering, Virginia Tech

1997:   Daniel Balint, Materials Science and Mechanics, Michigan State University

Minority Program - Undergraduate Research Interns

1992:   Samson Beyene, Mechanical Engineering, Virginia Tech
Juan Mejia, Mechanical Engineering, Virginia Tech

1993:   Kim Caldwell, Engineering Science and Mechanics, Virginia Tech
Dolon Silimon, Physics/Engineering, Clark Atlanta University
Paceon Walker, Physics/Engineering, Clark Atlanta University

1994:   Leslie Fowler, Mechanical Engineering, Virginia Tech
Dolon Silimon, Physics/Engineering, Clark Atlanta University
Kim Wilmers, Mechanical Engineering, Michigan Technological University

1995:   Brian Childs, Mechanical Engineering, California State Polytech. Univ. - Pomona
Wilbert Thurston, Mechanical Engineering, Virginia Tech

1996:   Dawn Scott Kinder, Chemical Engineering, North Carolina State University
Shane McNeil, Mech. Eng., California State Polytechnic University - Pomona
Kelly Yorg, Mechanical Engineering, Virginia Tech

Degrees Awarded

MS	Mahesh K. Subramaniam	May 1993
MS	David H. Kiel	June 1993
MS	Gary T. Fagan	September 1993
PhD	Pardeep Sensharma	December 1993
MS	Eric M. Flint	May 1994
MS	Peter Tappert	November 1994
MS	Tom Snyder	December 1994
PhD	Jeffrey S. N. Paine	December 1994
MS	Tom Kiesling	February 1995
MS	Adesh Bhargava	February 1995
PhD	Frederic Lalande	May 1995
PhD	Brett Pokines	May 1996
PhD	Maro Atalla	May 1996
MS	Roger Ellis	December 1996
PhD	Dino Sciulli	May 1997
PhD	Anton Sumali	July 1997

Honors Received

1996-1999 Prof. Daniel J. Inman named ASME Distinguished Lecturer

1996 Regional Research Award, National Society of Black Engineers

Mr. Brian Childs, a Mechanical Engineering major from California State Polytechnic University in Pomona, California, used his ARO summer undergraduate research project at Virginia Tech in competition at the National Society of Black Engineers national convention in March, 1996. Brian won first place in the Western Regional competition, and then went on to place second on the national level for his research at CIMSS involving a high-frequency vibration signature for non-destructive evaluation of complex precision parts.

1996 Prof. Craig A. Rogers named ASME Fellow

1995 College of Education Excellence in Education Award for Tour de TECH '95

Positions Currently Held by Students Supported

Dr. Frederic Lalande - Research Engineer, McDonnell-Douglas
Mr. Roger Ellis - Mechanical Engineer, Naval Surface Warfare Center
Mr. Fanping Sun - Associate Research Engineer, United Technologies Research Center
Mr. Jason Salmanoff - Project Engineer, CSA Engineering
Dr. Suwei Zhou - Engineer, Ford Motor Company
Dr. Daniel Cole - Instructor, Virginia Tech
Prof. Anton Sumali - Assistant Professor, Purdue University
Mr. Eric Flint - Project Engineer, CSA Engineering
Dr. Jeffrey S. N. Paine, Project Engineer, Garman Systems, Incorporated
Mr. David Kiel - Engineer, Siecor Corporation
Dr. Mark Lin - Assistant Professor, Clark Atlanta University

VI. Report of Inventions

Intellectual Property Disclosures

Jeffrey S. N. Paine and Craig A. Rogers, "Shape Memory Alloy Hybrid Composites for Damage Tolerant Structures," VTIP Disclosure No. 94-002.

Victor Giurgiutiu, Zaffir Chaudhry and Craig A. Rogers, "Hydraulically Amplified High-Displacement Induced-Strain Actuator (HAHDIS Actuator)," VTIP Disclosure No. 94-049.

Fanping Sun, Zaffir Chaudhry, Chen Liang and Craig A. Rogers, "Structural Integrity Monitoring with Hybrid Frequency-Time Domain Processing," VTIP Disclosure No. 94-051

Fanping Sun, Zaffir Chaudhry, Chen Liang and Craig A. Rogers, "Structural Integrity Monitoring Using PZT Sensor-Actuator and Electric Impedance Measurement," VTIP Disclosure No. 94-052.

Victor Giurgiutiu and Craig A. Rogers, "Large-Amplitude Rotary Induced-Strain (LARIS) Actuator," VTIP Disclosure No. 96-044.

Patents Awarded

"Impact and Perforation Resistant Composite Structures," Jeffrey S. N. Paine and Craig A. Rogers, U.S. Patent No. 5,614,305, March 25, 1997.